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## TABLE OF CONTENTS


| Section | | Page |
| --- | --- | --- |
| I. | Introduction | 1 |
| II. | "The Plasma Radiation Shield: Concept and Applications to Space Vehicles" | 1 |
| III. | Current Experiments | 2 |
| IV. | Studies of Toroidal Electron Clouds | 4 |
| V. | Computational Work | 6 |

## I. Introduction

This report covers progress made under Contract NAS8-20310 in the period 24 December 1966 to 23 March 1967. The relationship of the technical work reported here and work performed under Contract AF 49(638)-1553 continues to be as indicated in previous Quarterly Progress Reports.

During the present quarter a new paper on the Plasma Radiation Shield has been completed. In view of the comprehensive treatment of the whole concept in this paper, it is being distributed with this Quarterly Progress Report and should be considered to form a part of it. The abstract and Table of Contents of this paper appear in Section 2 of this report. Section 3 is devoted to a brief review of our current experiments. During the past quarter most of our effort has gone into the development and diagnostics capable of recording voltages from 100 KV up. Part of this work has been successfully completed and it is hoped to use these diagnostic tools in the toroidal apparatus at very high voltages in the near future. Section 4 discusses briefly the theory behind a new configuration for the Plasma Radiation Shield. The configuration is one in which the vehicle is essentially cylindrical with a narrow hole through its long axis around which a solenoidal coil is wound. The theory discussed in Section 4 shows why we expect (without at this time being sure) that the electron cloud in such a Plasma Radiation Shield would be largely confined to the vicinity of the hole. Considerable engineering advantages would accrue to the Radiation Shielding concept if these ideas turn out to be correct. These advantages are detailed in the attached paper. Section 5 reports the fact that the computational work already performed is presently being written up into a paper suitable for publication.

## II. "The Plasma Radiation Shield: Concept and Applications to Space Vehicles"

As stated in the Introduction, the paper "The Plasma Radiation Shield: Concept and Applications to Space Vehicles" is being distributed with this Quarterly Progress Report and should be considered to form a part of it. The Abstract and Table of Contents of this paper follow:

### Abstract

The Plasma Radiation Shield is an active device using free electrons, electric and magnetic fields for the purpose of shielding astronauts from energetic solar flare-produced protons. The concept of Plasma Radiation Shielding is reviewed in the light of current studies. The available evidence indicates that the concept is physically sound, but

important practical questions remain in at least two areas: these have to do with establishment and control of the extremely high voltages required, and with integration of the concept into a realistic space vehicle design.

Table of Contents

I. Preface
II. Space Radiation Shielding
III. Plasma Radiation Shielding Concept
IV. Voltage Selection in the Plasma Radiation Shield
V. Vehicle Configuration Possibilities
VI. Superconducting Coil System
VII. Vacuum Requirements
VIII. Other Systems Considerations
IX. Conclusions
X. Acknowledgment
XI. References
Appendix: Status of Work on the Electron Cloud

This paper will be presented orally at the meeting of the American Nuclear Society, San Diego, June 11-15, 1967, and will be submitted to the Journal of Spacecraft and Rockets.

## III. Current Experiments

### A. High Potential Diagnostics

The quarterly Progress Report for December 1966 (Contract NAS8-20310) reported on recent probe measurements obtained from the toroidal apparatus. From these experiments it was not expected that probe measurements will be useful at voltages significantly in excess of 100,000 volts. Hence, new high potential diagnostics are being developed.

#### 1. Charge exchange diagnostics.

The Quarterly Progress Report for September 1966 outlined the physical principles involved in a new charge exchange diagnostics technique to be applied to the toroidal apparatus. The design characteristics of a proposed method for implementing the charge exchange diagnostic concept was contained in the December 1966 Progress Report. During the past quarter this apparatus has been assembled and given initial testing. While clear, charge exchange pulses have been observed by this equipment, spurious noise from the induction of the toroidal magnetic field has been a problem. Complete electrical isolation of the charge exchange detector from the torus vacuum vessel now seems desirable to eliminate ground loops. The necessary modifications to the detector housing are now being planned and will be tested during the next quarter.

The present method for sensing the high energy charge exchanged neutral flux from the torus depends upon a relatively accurate understanding of the ion orbits in the torus. Design of an instrument depending on these ion orbits was necessary to produce the hardened charge exchanged neutral flux spectrum required by the particle detector's counting rate limitations. Another possibility for circumventing these detector limitations with a minimal dependence on the details of the ion orbits is to use a "stripping foil" and a curved plate electrostatic ion energy analyzer together with the present particle detector. Recent discovery of a ready source of stripping foils has made this approach possible. The design characteristics of this analyzer are now being worked out and if found promising, such an instrument will be assembled and tested during the next quarter.

### 2. Image charge diagnostics

Another method for determining the potential well depth of the torus has been developed and tested during the past quarter. This method is based upon the observation that the electric field of the unneutralized electrons in the torus induces a surface charge on the conducting walls of the torus. By insulating a section of this wall (image charge button) from ground the surface charge induced on the wall can be measured. Because of electron loss to the walls during the inductive charging cycle, it has been found necessary to bias the insulated image charge button negative with respect to the surrounding wall sections. As the negative bias is increased, a plateau is reached which yields the correct image charge. Using this plateau, good agreement has been obtained between total image charge measurements and probe voltage measurements. It is hoped that during the next quarter a detailed comparison between the instantaneous image charge current during inductive charging and the final radial charge distribution in the torus can be obtained. Such an agreement would permit future use of instantaneous image current measurements to infer the actual potential well depth.

## B. Toroidal Experiment

Previous Quarterly Progress Reports have described the toroidal apparatus and the electrostatically shielded injection arrangement now in use. This apparatus has been used for two major purposes during this quarter. The first is that of proof testing and calibration of the high potential diagnostic techniques described above.

The second area of effort has been to determine the fraction of electronic charge injected that is accepted by the torus (i.e., the charge producing the potential well). Though still preliminary, this data indicates that a significant fraction of the charge is lost to the vacuum vessel walls — often 60% to 80% of the injected charge. This loss may be due to an instability such as described in Quarterly Progress Report for December 1966 (NAS8-20310) or perhaps due to noise resulting from a poor configuration of the cathode structure (i.e., filament). Experimental evidence exists in the literature on crossed-field electronic beam tubes which shows similar anomalous electron losses. Much of this literature points to the cathode structure as being quite important in determining the amount of anomalous loss. A major effort will be directed in this area of electron injection during the next quarters.

A new filament has just been installed at this writing. The filament to anode spacing (h) has been changed from that of previous experiments. This new filament will thus serve to check the dependence of the apparatus gain on the filament to anode spacing. The gain is thought to depend upon $1/h^2$.

## IV. Studies of Toroidal Electron Clouds

An outstanding need in connection with the Plasma Radiation Shield is the calculation of detailed electron distributions around typical Plasma Radiation Shields. While the general principles of this calculation have been clear for some time, certain important difficulties have prevented the undertaking of detailed calculations up to this moment. During the past quarter the problem underlying these difficulties has been clarified. This clarification has furthermore resulted in an important conceptual innovation. This is the solenoidal shaped Plasma Radiation Shield discussed in the attached paper. This configuration is likely to have an electron cloud strongly concentrated towards the interior of the vehicle (the region of high magnetic field). The engineering advantages that would accrue if this guess turns out to be correct is discussed in the attached paper.

In this section we give a brief outline of the theory underlying the problem of calculating electron distributions around the Plasma Radiation Shield.

It has been thought since the first conception of the Plasma Radiation Shield that the electron distribution around the Plasma Radiation Shield would be such as to make the individual magnetic field lines coincide with the electrostatic equipotentials. This condition was suggested by the observation that the electrons must and can flow along the field lines in such a way as to nullify any potential gradients parallel to the magnetic field that may exist. As we shall see, this hypothesis may not be fully tenable.

Let us describe an axisymmetric magnetic field by a function $\psi(r, z)$ ($r$ and $z$ are cylindrical polar coordinates). The radial and axial components of the magnetic field will be given by

$$B_z = \frac{1}{r}\frac{\partial\psi}{\partial r} \quad ; \quad B_r = -\frac{1}{r}\frac{\partial\psi}{\partial z} \tag{4.1}$$

$\psi$ is a quantity proportional to the magnetic flux exterior to a given field line. A displacement in which $\psi$ remains constant is described by

$$d\psi = \frac{\partial\psi}{\partial r}\, dr + \frac{\partial\psi}{\partial z}\, dz = r\,[B_z\, dr - B_r\, dz\,] = 0 \tag{4.2}$$

from which it follows that

$$\frac{dr}{dz} = \frac{B_r}{B_z} \tag{4.3}$$

This shows that the lines $\psi$ = constant do in fact coincide with the magnetic field lines. Let us now suppose that the electrostatic potential $\phi$ is, as originally hypothesized, a function of $\psi$ only. Thus

$$\phi = \phi(\psi) \tag{4.4}$$

By differentiation the electrical field is given by

$$E_r = -rB_z\phi' \quad ; \quad E_z = rB_r\phi' \tag{4.5}$$

Notice that $\underset{\sim}{E} \cdot \underset{\sim}{B} = 0$ as indeed it must. Taking the divergence of Eq. (4.5) gives the electron number density $n$ as follows:

$$n = \frac{\epsilon_0}{e}\,[\,r^2B^2\phi'' + 2B_z\phi'\,] \tag{4.6}$$

It is this equation for the number density that is at the root of the problem. Assuming that $\phi'$ and $\phi''$ are positive (this will generally be the case), the first term in Eq. (4.6) is necessarily positive, but the second term can change sign according to the sign of $B_z$. The two terms will generally add in the interior of a coil where the magnetic field is strong and subtract on the same field line outside the coil where the magnetic field is weak. The problems arise from the fact that for interesting choices of the function $\phi(\psi)$ the number density can become negative far away from the coil. Such a result is physically unrealistic, but has a certain meaning as follows: magnetic field lines passing through the coil close at a large distance. If a given flux tube carries one unit of negative charge, the condition that the flux tube be an equipotential can sometimes require that two units of negative charge appear in the high field region and one unit of positive charge appear in the low field region. This phenomenon, which is present only in three-dimensional cases, is, of course, impossible, and the next question is to find out what will happen.

To approach this question let us consider a positively charged Plasma Radiation Shield and a single negative charge on some magnetic field line. This charge will very clearly come to equilibrium at that point of the field line nearest to the Plasma Radiation Shield, a point which will coincide with the highest field strength on that field line. If this charge is now divided into two, these two charges will find a balance between their mutual repulsion and attraction of the Plasma Radiation Shield. Proceeding in this way suggests that with a given number of electrons on a flux tube these will concentrate in the high magnetic field region and leave a vacuum in the low magnetic field region. In the vacuum there is, of course, no requirement that the magnetic field lines be equipotentials. In fact, the equipotentials will fall inside the magnetic field lines in this region. At the boundary between the electron cloud and the vacuum the equipotentials must be tangent to the magnetic field. A preliminary picture of this concept is given in Fig. 3.4 of the attached paper, but it must be emphasized that there are presently neither detailed calculations nor experiments to back up this picture. The calculations are greatly complicated by the existence of an undetermined free surface.

In view of the importance of obtaining a correct understanding of this problem, it is expected that the necessary computations will be actively undertaken during the coming quarter.

## V. Computational Work

Although several new computational simulations of electron motion are under discussion, none is presently in progress. Work is progressing on a paper describing the results achieved so far under the title "Computer Experiments on Low Density Crossed Field Electron Beams." It is expected that this paper will be completed during the coming quarter. The abstract is as follows:

## Abstract

The motions of thin and thick low density ($q = \omega_p^2/\omega_c^2 \ll 1$) crossed-field electron beams have been studied on the computer. Theoretical indications that such beams can be stable or unstable depending on the geometrical and electrical arrangements are supported, and the large amplitude behavior of unstable configurations is found. In particular, thick, periodic beams can be quite stable against perturbations of the diocotron type.